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Project Title: **Using Dense Nodal Deployments to Characterize the Structure of the San Gabriel and San Bernardino Basins, Southern California: Collaborative Research with Louisiana State University and California Institute of Technology**

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Using Dense Nodal Deployments to Characterize the Structure of the San Gabriel and San Bernardino Basins, Southern California: Collaborative Research with Louisiana State University and California Institute of Technology

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Key words: San Bernardino basin, San Gabriel basin, basin amplification, San Andreas fault, seismic hazard, Los Angeles area.

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ABSTRACT

Our goal is to provide accurate estimates of the depths and shapes of the northern sedimentary basins in the northern Los Angeles area that are expected to amplify and channel seismic waves from a San Andreas fault rupture into the densely populated Greater Los Angeles area. We are using short period seismic data collected along 10 transects in 2017-2019 to map the shape of the San Gabriel and San Bernardino basins. Receiver functions are being computed for the 2018-19 dataset that will fill in the gaps in the data coverage from the published 2017 dataset. The receiver function results will be compared to images of crustal reflectivity determined through autocorrelation of the data. We are additionally cross correlating node-to-node stations and all nodal stations with nearby SCSN stations to develop an independent 3-D large-scale shear-wave velocity model and higher resolution 2D shear-wave velocity structure along the individual seismic lines. The estimates of shear-wave velocity will be used to constrain the depth conversion of the receiver functions. We are developing algorithms to use the basement surface and other mid-crustal layers obtained from receiver functions along the 10 profiles as ground truth to forward model the gravity data in the study area. This will provide a 3-D basement surface that is also compatible with our 3-D large-scale shear wave velocity model.

INTRODUCTION

The San Gabriel and San Bernardino basins are two wedge-shaped basins located adjacent to the San Andreas and San Jacinto fault zones (Fig. 1). Earthquake ground motions in the greater Los Angeles area are known to be affected by basin amplification and the channeling and focusing of seismic energy as it passes through the San Gabriel and San Bernardino basins in the northern part of this region (Frankel, 1994; Olsen et al., 2006; Graves, 2008). To help increase the accuracy of ground shaking models for the Los Angeles area, various studies have provided improvements to the shape of the northern basins, e.g., using gravity modeling (Anderson et al., 2004), through finite difference simulations of ground motion (Graves, 2008) and with two active source seismic profiles across the San Bernardino basin (Catchings et al., 2008). However, the current SCEC velocity model, CVM-S4.26 still lacks sufficient detail and does not accurately represent the actual basin structure. Furthermore, simulated ground motions from a San Andreas fault earthquake are four times smaller than those measured with ambient noise cross-correlations, which is likely due to inaccuracies in the basin shape (Denolle et al., 2014).

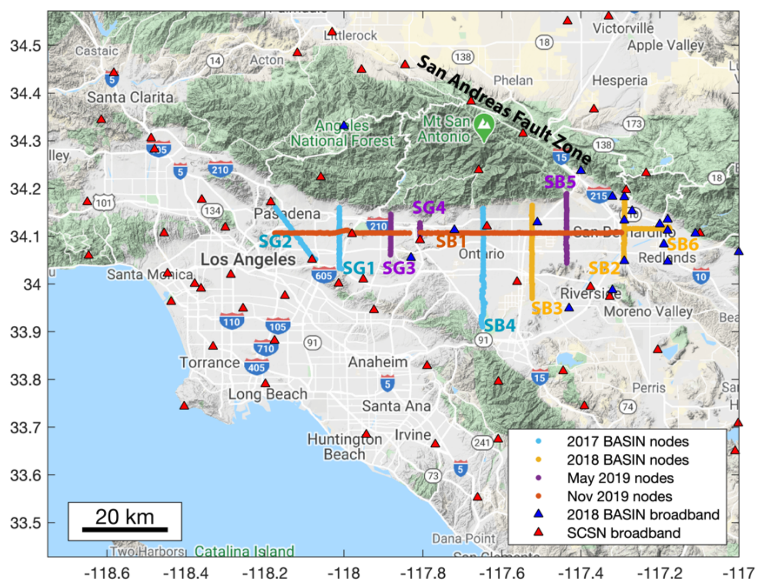


Figure 1. *Location map showing the BASIN surveys color-coded by the deployment year. The red triangles are the Southern California Seismic Network (SCSN) stations with available data. Active faults from the 2010 Fault Activity Map of California (Jennings and Bryant, 2010) are shown. The table below lists the number of nodes deployed along each profile and the deployment year.*

Year	Lines	# Nodes in each line
2017	SG1, SG2, SB4	60, 50, 92
2018	SB2, SB3, SB6	56, 85, 30
May 2019	SG3, SG4, SB5	34, 15, 60
Nov 2019	SB1	262 (78 km long)

This study provides further constraints on the geometry and seismic structure of the San Bernardino and San Gabriel basins using 10 basin crossing profiles that cover the region with a dense inline station-spacing of ~250 m and ~35 days of continuous recording (Fig. 1). The data were collected over a three year period, 2017-2019 and data along four of these profiles were collected in 2019, during the current project period. The SG3, SG4 and SB5 profiles were collected in May 2019 and SB1 was collected in November (purple and dark orange stations in Fig. 1). An example of the data recorded along the east-west SB1 profile is shown in Figure 2 with the location of the profile shown in Figure 1. Additional examples and other data products such as cross correlations are available at: http://web.gps.caltech.edu/~clay/BASIN/BASIN.html.

Our published results (Clayton et al., 2019; Clayton et al., 2020; Liu et al., 2018;) show that in an urban setting with high cultural noise levels, the new type of array can be successfully used to identify the detailed basin scale structure needed for realistic high frequency ground motion simulations. In this study, our goal is to expand and refine these results by producing an integrated 3-D map of the basement beneath the San Bernardino and San Gabriel basins and an updated 3-D velocity model of the region that captures basin-scale changes in seismic velocities that are currently missing in the Southern California Earthquake Center (SCEC) Community Velocity Models.

DATA AND METHOD

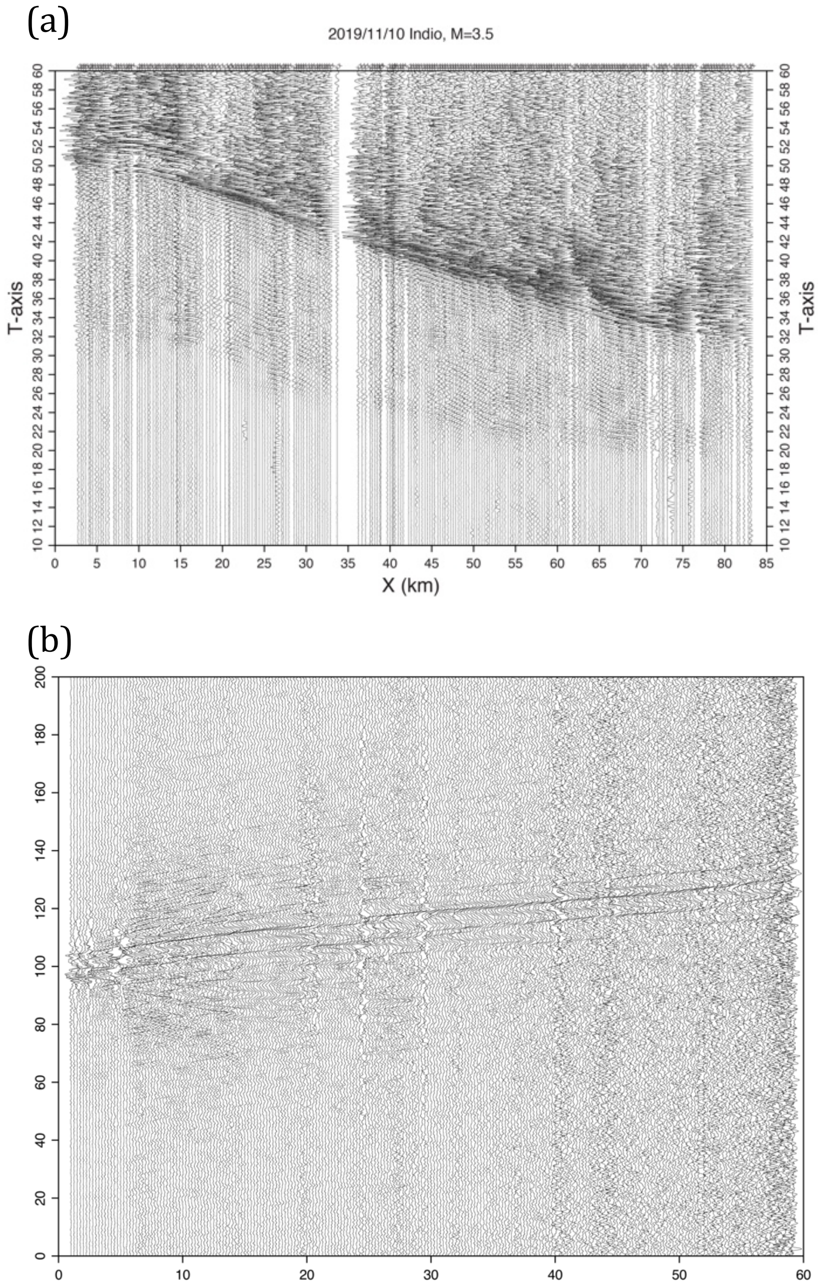


Figure 2. *(a) Example of the vertical component nodal data from the east-west oriented SB1 deployed in November 2019. The recordings are from a regional M 3.5 earthquake that occurred in Indio, California. For presentation purposes, a bandpass filter (0.1-1 Hz) was applied. The P wave arrival and the surface waves are evident. Distance increases along the profile from west to east. (b) ZZ cross correlations between the SCSN broadband station PASC and the SB1 nodes. The correlations are bandpass filtered (0.1-1 Hz), and "zero" lag is at 100 sec on the y-axis. The traced are spaced at a uniform distance of 0.25 km along the x-axis, which is only approximately true. Rayleigh waves are observed up to ~60 km profile distance. Other SB1 plots including cross correlations and plots showing local, teleseismic, and Ridgecrest events are available at: http://web.gps.caltech.edu/~clay/BASIN/BASIN-SB1.html. Cross correlations are provided by Yida Li.*

With the availability of dense arrays of nodal seismometers, i.e., autonomous instruments that are easy to deploy and can record continuously for ~35 days, passive seismic sources can be exploited using traditional techniques such as receiver functions (e.g., Ward and Lin, 2017) to image the subsurface at the basin scale and to image fault zone structure. This is achieved by a denser sampling of the seismic wavefield. For the same reason, the traditional multi-year widely-spaced broadband deployments are at a disadvantage particularly in noisy settings such as the Los Angeles basin (Ma and Clayton, 2016). Using some of the earliest BASIN profiles, we previously demonstrated that nodal data can provide robust receiver functions even in an urban setting with high cultural noise levels and also compare the waveforms, frequency spectra, spectrograms and receiver functions from broadband and nodal data (Liu et al., 2018). We further used receiver functions computed from our 2017 BASIN dataset comprised of an ~35 day period of recording along three profiles in the San Gabriel and San Bernardino to map the depth and shape of the sediment-basement interface and to identify possible deep fault offsets. Here we continue this analysis by computing receiver functions for six more BASIN profiles collected in 2018 and May 2019. Results for the SB2 and SB3 profiles are shown in Figure 3 and SG3 and SG4 are shown in Figure 4. We use the frequency domain deconvolution method of (Di Bona, 1998).

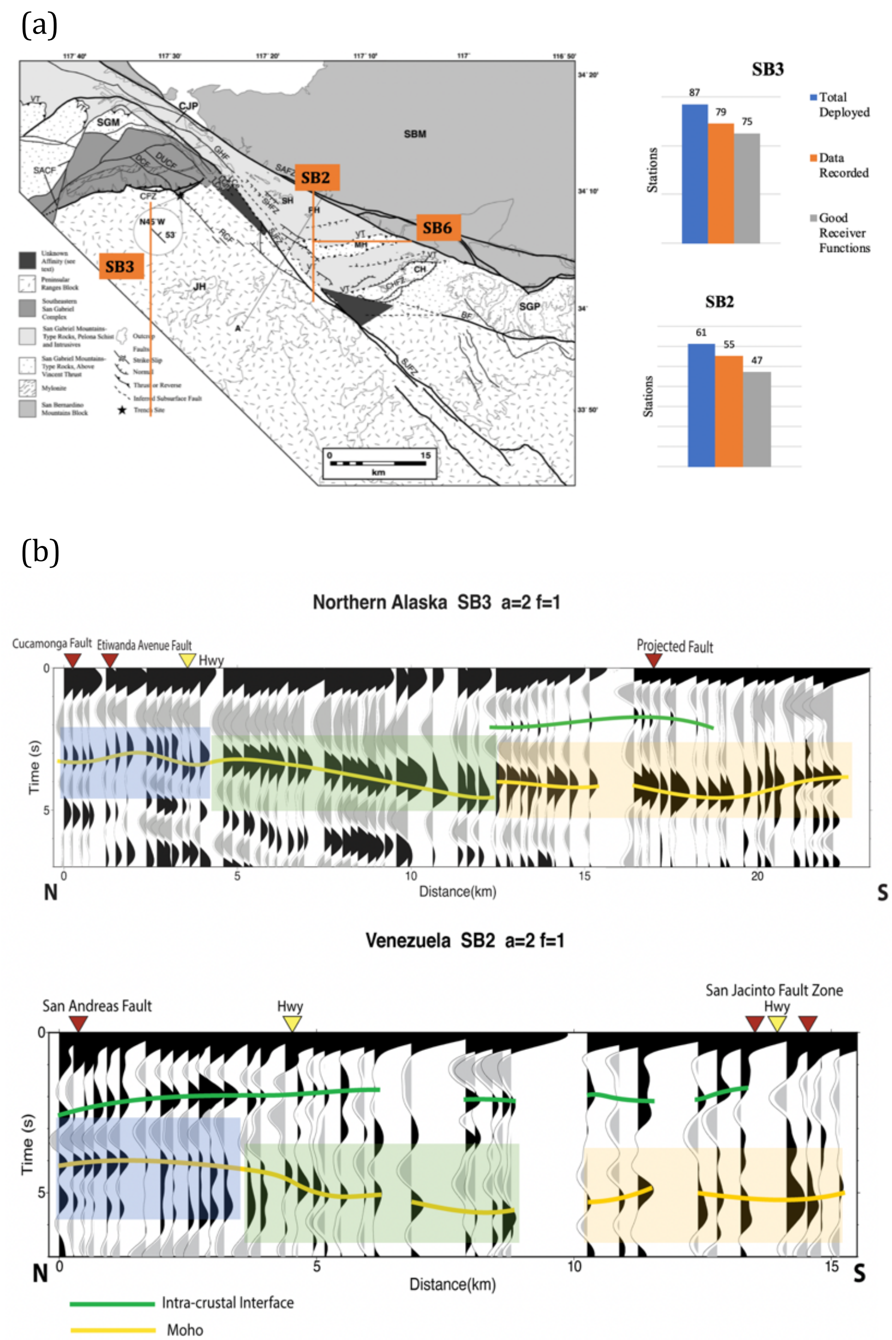
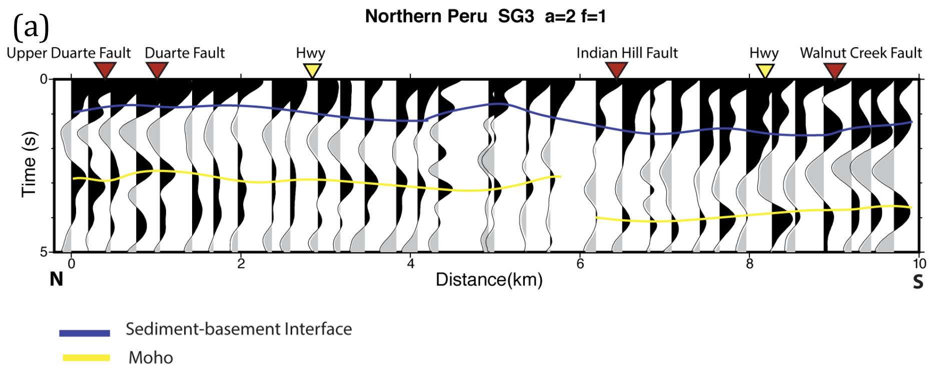


Figure 3. *(a) Map with basement types from Anderson et al. (2004) overlain with the 2018 BASIN profiles marked with orange lines. Histograms to the right of the map show the number of stations for SB3 and SB2 (blue), and the number of good receiver functions obtained in each case (orange). (b) 1 Hz receiver function profiles for SB3(top) and SB2 (bottom) showing a clear Moho conversion (yellow) and an intracrustal interface (green). The character of the receiver functions changes along the profiles, but parts of the two profiles show some similar characteristics, which are marked with different color rectangles. We interpret the different character of the receiver functions as possibly due to different crustal blocks that may exist along the profiles. Note the amplitudes of the receiver functions to the south of the Projected Fault in SB3 are plotted at twice the amplitde of the other receiver functions in this profile. Profiles from Ritu Ghose.*

Our receiver function results are, however, provided in time and a depth conversion requires using surface-wave velocities to develop an accurate velocity model. To obtain a 3-D shear-wave velocity model for the region, we have produced ambient noise cross-correlations between the SCSN stations and the various basin-crossing nodal profiles. An example of these cross correlations is shown in Figure 2b. Ma and Clayton (2016) showed for the 40 day dataset (73 broadband stations) from the LASSIE experiment that correlations between the LASSIE array and the SCSN produced a large-scale 3-D velocity structure for the Los Angeles basin. In our case, we have correlated the ~35 days of data collected along the 2017-2019 SG and SB lines (~744 stations) with the dozen or so SCSN stations around the northern basins. The result is a high density of cross ray paths in the basin. In addition to a large-scale 3-D velocity model for the study area, we have produced high-resolution shear-wave velocity models along each of the individual profiles using ambient noise recordings. This approach will help us interpret both fault geometry and basin shape.



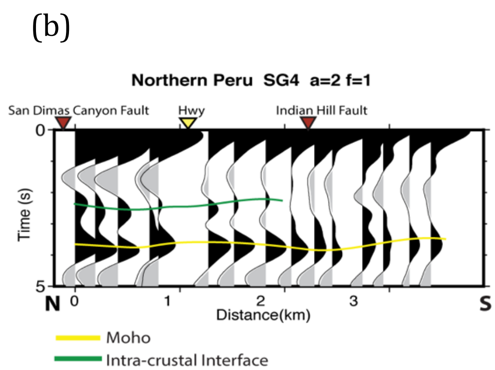


Figure 4. *(a) 1 Hz receiver functions along the SG3 profile in the San Gabriel basin showing the sediment-basement interface marked with a dark blue line and a possible deep offset near the location of the Indian Hill fault. (b) The 1 Hz receiver functions along the SG4 profile located farther east do not show a similar offset as in SG3. See Fig. 1 for the locations of the profiles. Profiles from Ritu Ghose.*

RESULTS

Receiver Functions

Our analysis shows a large number of good receiver functions with high signal-to-noise ratio (histograms in Fig. 3a) and a high level of detail revealing the Moho P-to-S conversion, and intracrustal and sediment-basement interfaces. These features can be traced across the different profiles in both the San Bernardino (Fig. 3) and San Gabriel basins (Fig. 4). In the San Bernardino basin, Anderson et al. (2004) have interpreted Peninsular Ranges basement rocks along our SB3 profile and mainly Pelona Schist along SB2 (Fig. 3a) based on gravity modeling. Our results in this basin, however, show the character of the receiver functions changes along the profiles, but parts of the SB2 and SB3 profiles show some similar characteristics in terms of the amplitudes and frequencies of the receiver functions. These matching characteristics are marked with colored rectangles in Figure 3b. We interpret these patterns in the receiver functions as possibly due to different crustal blocks that may exist along the profiles. This hypothesis will be tested with the integrated receiver function-gravity modeling that we are doing.

In the San Gabriel basin, we have two profiles, SG3 and SG4 that cross the mainly eat-west striking Indian Hill fault. The Indian Hill fault has inferred left-slip and may also be a groundwater barrier with discontinuous water levels observed across the fault (e.g., Hauksson and Jones, 1991 and references therein). Along SG3 there is a deep offset of the Moho close to the surface location of the Indian Hill fault (Fig. 4a), but a similar offset is not observed along SG4 (Fig. 4b). It is not clear whether this deep offset along SG3 is associated with the Indian Hill fault or a fault splay in the region. The (M_L=4.6) 1988 and (M_L=5.2) 1990 Upland earthquakes and aftershocks occurred between the inferred surface traces of the San Jose and Indian Hill faults and the mapped surface trace of the Cucamonga fault, with the San Jose fault, an 18-km-long concealed fault interpreted as the causative fault by Hauksson and Jones (1991). These authors conclude that the presence of 14 km of unbroken fault, the abrupt temporal termination of deep aftershocks, and the constant stress state all suggest that a future moderate-sized earthquake (M_L=6.0-6.5) on the San Jose fault is possible with a rupture length of at least 14 km and possibly 18 km. Combining the receiver function results with the S-wave velocity model and gravity modeling will allows us to provide constraints on the fault dip, and geologic structure along these profiles.

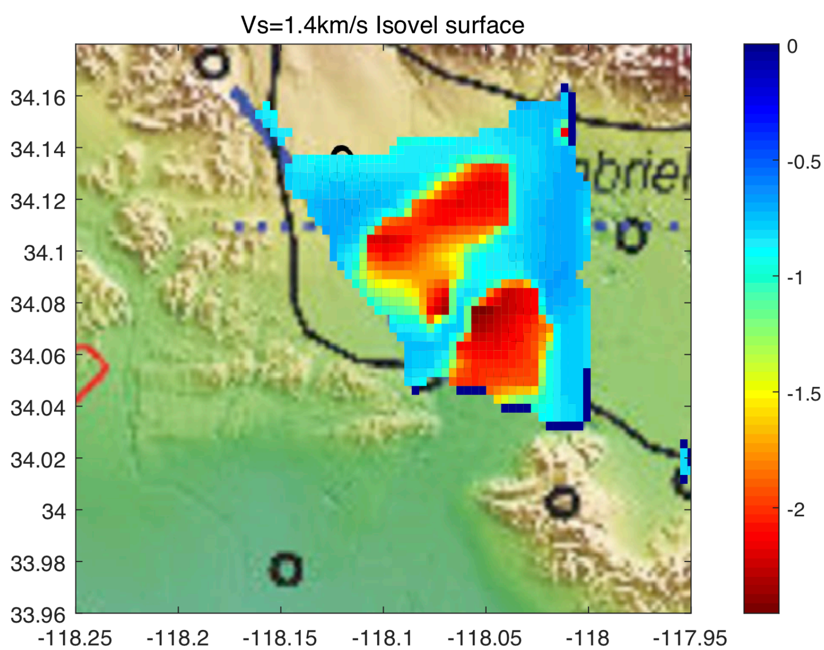


Figure 5. *Preliminary estimate of basement depths determined from our 3-D shear-wave velocity model based on the analysis of SG1 and SG2. The depths are determined by selecting an iso-velocity surface of 1.4 km/s which may not represent the sediment-basement interface everywhere in this region. Two sub-basins (red areas show the deepest parts) may exist in between the SG1 and SG2 profiles. Figure from Yida Li.*

3-D V_s model San Gabriel Basin

To obtain our 3-D shear-wave velocity model, we first compute multicomponent ambient noise cross correlations between SCSN broadband stations and our nodal array (station locations in Fig. 1) and node-to-node cross correlations. We then apply a new technique that allows us to isolate fundamental and first higher mode Rayleigh wave dispersion curves (Li et al., 2019). This step results in a more accurate velocity model because the higher mode dispersion curve is not misidentified as the fundamental mode. Our 3-D S-wave velocity model provides a detailed image of the basin structure in the region. A 1.4 km/s iso-velocity surface extracted from our preliminary 3-D velocity model is expected to give a sense of the shape of the basin in the San Gabriel Valley and is shown in Figure 5. The basement depth estimates show two sub-basins that are located between our SG1 and SG2 profiles. Further cross correlations will include the newly collected east-west oriented SB1 line from November 2019, which will allow us to determine whether these basins extend eastward and will address the question of basin connectivity within the region and how efficient the basins may be at channeling seismic energy into the Downtown Los Angeles area.

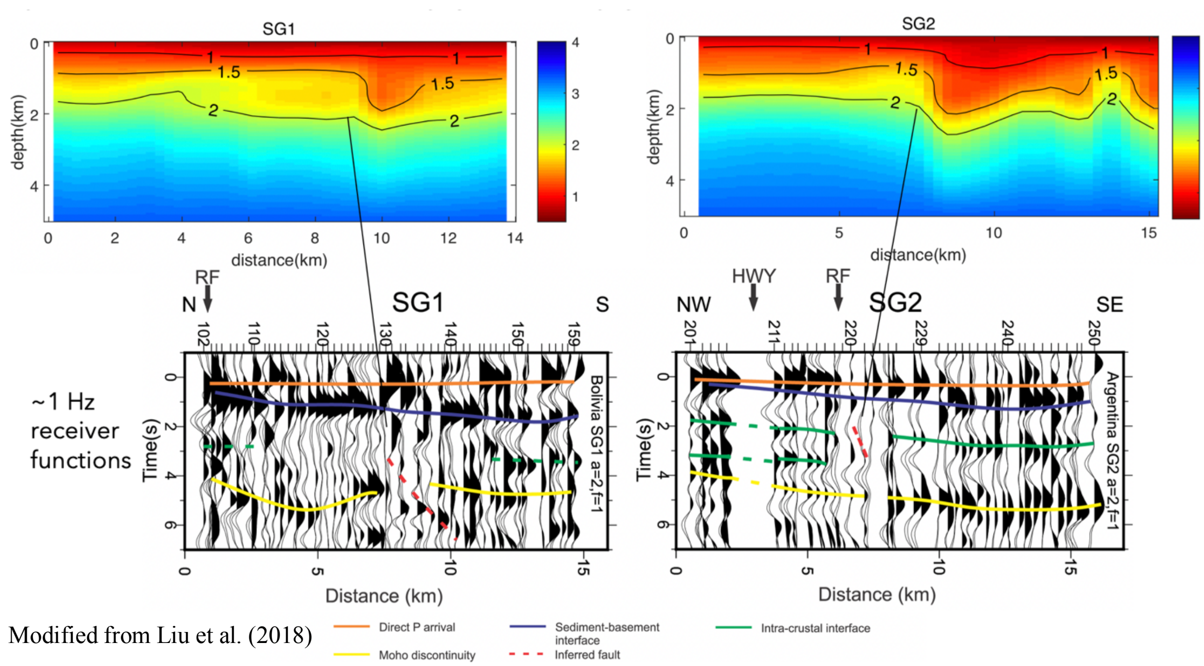


Figure 6. *Comparison of the shear-wave velocity profiles for SG1 and SG2 to receiver function results from Liu et al. (2018). The possible deep fault offset interpreted in the receiver function profiles (dashed red lines) may also be evident in the shear-wave velocity models. Velocity profiles from Yida Li.*

Comparing our S-wave velocity models along the SG1 and SG2 profiles to previously published results shows that the deep fault offset in the receiver functions appear to be co-located with steps or abrupt changes in the velocity models (Fig. 6) suggesting that the basin structure may be fault controlled. If this is the case, abrupt lateral changes in our velocity model may also be used to identify concealed or unmapped faults in the region that are important for seismic hazard.

Another interesting result is comparing the velocity profile at the Ferris well to the sonic and density logs presented in (Brocher et al., 1998). Those authors identify a velocity inversion in the

San Gabriel valley that we have imaged in the Ferris well (right panel in Fig. 7). They analyzed three wells in the San Gabriel Valley and other wells in the Los Angeles basin and conclude that a prominent P- and S-wave low-velocity zone within the Cenozoic basin fill underlies the entire San Gabriel Valley and possibly the margins of the Los Angeles basin. This low-velocity zone should produce large-amplitude guided and converted arrivals at low frequencies of 1 to 2 Hz (Brocher et al., 1998). These authors note that mapping its extent may allow us to better understand the spatial distribution of strong ground motions in the Los Angeles area.

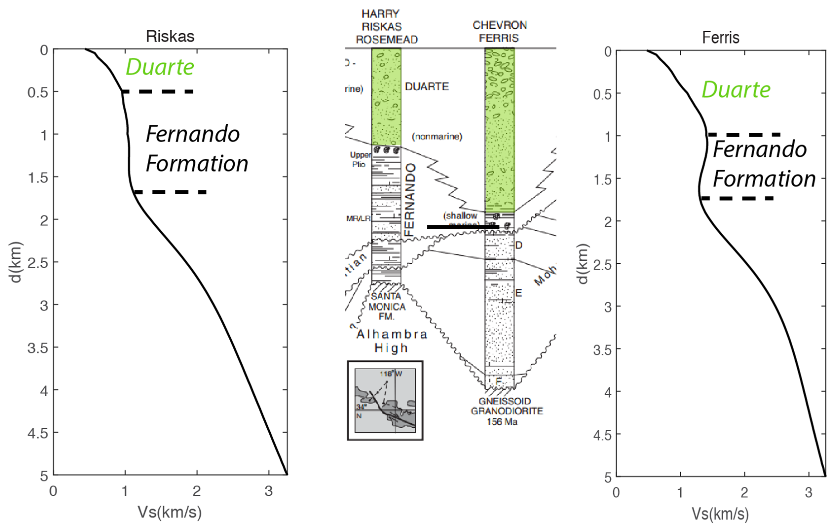


Figure 7. *Comparison of the wellbore stratigraphy of the Riskas and Ferris wells from Yeats (2004) to shear-wave velocity profiles extracted from our 3-D velocity model. The location of the Ferris well is taken from Brocher et al. (1998) and is shown in the map in Fig. 8. Changes in the slope of the velocity profiles are interpreted as related to changes in lithology from the largely Duarte non-marine conglomerates to the marine Fernando formation. At the Duarte well, we observe a velocity low similar to the low velocity zone that was previously interpreted by Brocher et al. (1998) to underlie the San Gabriel Valley. Velocity profiles from Yida Li.*

3-D V_s model San Bernardino Basin

The final phase of the BASIN nodal deployments was completed in November 2019 with the acquisition of the SB1 profile (262 nodes; Persaud et al. 2019). We are currently computing cross-correlations between the SCSN stations and nodes that were deployed in the San Bernardino basin and node-to-node cross-correlations, which will be used to determine a 3-D velocity model for the basin. Examples of the correlation functions show clear Rayleigh waves (example in Figure 2b) and Love waves (TT correlations are available at http://web.gps.caltech.edu/~clay/BASIN/BASIN-SB1.html). Extracting Love waves from the ambient noise cross-correlations was not possible with the San Gabriel basin data, but will be possible for the San Bernardino basin profiles and will provide additional constraints on the 3-D shear-wave velocity model.

Gravity Modeling

We will use our 3-D Shear-wave velocity model along with the borehole P- and S-wave velocities and densities in the region from Brocher et al. (1998) to constrain the depth conversion of the receiver functions. Forward modeling of the basement surface and other mid-crustal layers obtained from receiver functions along the ten profiles will be compared to the observed gravity data in the study area (Fig. 8) with the misfit reduced to find the earth model that best fits all of the data. This will provide a 3-D basement surface that is also compatible with our 3-D large-scale shear-wave velocity model.

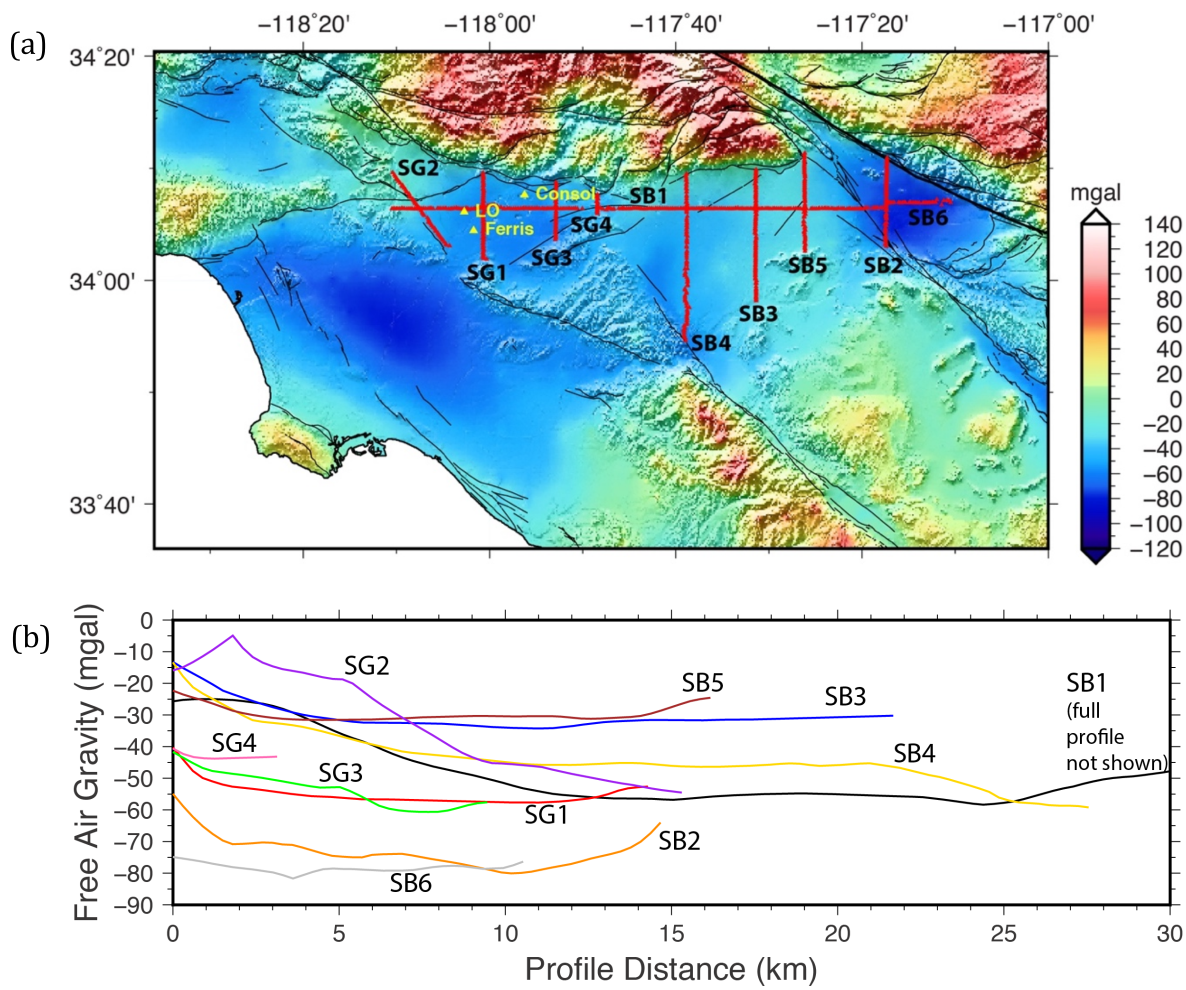


__Figure 8.__ (a) Colored-grid of the free air gravity anomaly of the greater Los Angeles area draped over the topography. Small red triangles are the BASIN stations. Yellow triangles are the San Gabriel basin wells that were analyzed in Brocher et al. (1998). (b) Free air gravity anomaly along the 10 BASIN profiles. The full SB1 profile is not shown for clarity. Gravity data were obtained from the PACES database.

CONCLUSIONS

We have made a number of major steps towards a comprehensive structural model of the San Gabriel and San Bernardino basins that will integrate basement estimates obtained from seismic data collected at a dense station spacing of ~250 m along multiple basin-crossing profiles and fits the observed gravity in the region. The project will make a significant contribution to the Earthquake Hazards Program under *SC Element I*, i.e., to develop new, improved, or alternative models of 3D fault, seismic velocity and seismic attenuation structures with the integration of these models within the existing SCEC Community Fault and Velocity Models, and to develop methods for incorporating shallow physical properties (e.g. Vs30) into these 3D models. We are currently developing and testing a new method for merging high-resolution models with regional scale SCEC Community Velocity models. Our final hybrid 3-D model will be readily available for the refinement of future seismic hazard maps.

PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS AWARD

Clayton, R. W., Persaud P., Denolle, M., and Polet J. (2019), Exposing Los Angeles's shaky geologic underbelly, *Eos, 100,* https://doi.org/10.1029/2019EO135099. Published on 10 October 2019.

Clayton, R. W. (2020), Imaging the Subsurface with Ambient Noise Autocorrelations. *Seismological Research Letters* ; 91 (2A): 930–935. doi: https://doi.org/10.1785/0220190272

Li, Y., Clayton, R. W. amd Jia, Z. (2019). S-wave velocity model from ambient-noise surface-wave tomography in the San Gabriel and San Bernardino Basins. Poster Presentation at 2019 SCEC Annual Meeting.

Persaud, P., Clayton, R. W., Ghose, R., Li, Y., Wang, X., Denolle, M. A., Polet, J., *et al.* Seismic Structure Beneath Los Angeles from the BASIN Experiment (2020), Oral Presentation at 2020 Seismological Society of America Annual Meeting.

Persaud, P., (2020), IRIS webinar: "Urban Seismology in Megacities: the Los Angeles BASIN Experiment" https://www.youtube.com/watch?v=jtrAuY3Vwew

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